NACA TN 2039

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

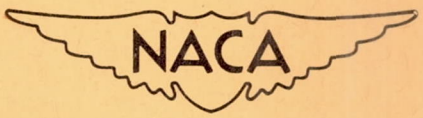
TECHNICAL NOTE 2039

INVESTIGATION OF FRETTING CORROSION BY MICROSCOPIC OBSERVATION

By Douglas Godfrey

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

PROPERTY FAIRCHILD
ENGINEERING LIBRARY



Washington
February 1950

MAR 1 0 1950

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2039

INVESTIGATION OF FRETTING CORROSION BY MICROSCOPIC OBSERVATION

By Douglas Godfrey

SUMMARY

An experimental investigation using microscopic observation of the action was conducted to determine the cause of fretting corrosion. Glass and other noncorrosive materials, as well as metals, were used as specimens. A very simple apparatus vibrated convex surfaces in contact with stationary flat surfaces at frequencies of 60 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

The observations and analysis led to the conclusions that fretting corrosion was caused by the removal of finely divided and apparently virgin material due to inherent adhesive forces, and that its primary action is independent of vibratory motion or high sliding speeds. The fretting corrosion of platinum, glass, quartz, ruby, and mica relegated the role of oxidation as a cause to that of a secondary factor. Fretting corrosion occurred to clean nonmetals and metals readily and glass microscope slides and steel balls provided an excellent method for visual studies.

INTRODUCTION

Fretting corrosion is surface failure that may occur when closely fitting machine components are vibrated. The designation may be inaccurate but will be used herein. The phenomenon of fretting corrosion (herein applied to surface failure that may occur when closely fitting machine components are vibrated) is principally characterized by surface stain, corrosion, pitting, and the generation of oxides, as described in detail in references 1 and 2. The determination of the cause of fretting corrosion has been the object of several research programs. The research reported in reference 2 supports Tomlinson's theory of molecular attrition (reference 3) that indicates that the cause of fretting corrosion is a physical action, or specifically, the disintegration of the metal surface is due to "molecular plucking." More recently, chemical action has been reported to be of primary importance (reference 4).

Other investigators (for example, references 5 and 6) have advanced electrolytic, abrasion, welding, and fatigue theories to explain the action that produces fretting corrosion. These theories are divergent and more evidence is needed to make any one theory generally acceptable.

The failure of certain aircraft parts due to fretting corrosion has produced new incentive to solve the problem of the prevention of the phenomenon. Antifriction bearings subject to rotational oscillation and side-thrust vibration experience the greatest amount of fretting corrosion and such parts as connecting rods, knuckle pins, splined shafts, and clamped and bolted flanges suffer deleterious effects (reference 1).

The research reported herein was conducted at the NACA Lewis laboratory to observe and to analyze the action of fretting corrosion in its initial stages in order to determine its cause. Inasmuch as the limits of mechanical factors such as load, frequency, and amplitude have been established (reference 2), this investigation was limited to microscopic observation, debris analysis, and surface analysis of fretting-corrosion areas. The nonmetallic materials, glass, quartz, ruby, and mica, and the metal platinum were used as specimens because their noncorrosiveness would indicate whether the primary action was physical or chemical; in addition, the nonmetallic materials eliminated the possibility of welding, simplified the debris analysis, and in some cases permitted microscopic observation of the action.

Fretting corrosion was induced by a very simple apparatus, which vibrated a convex (usually spherical) surface in contact with a flat surface at frequencies of 60 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

APPARATUS, MATERIALS, AND PROCEDURE

A photograph of the apparatus is shown in figure 1. The vibrating action of 60 cycles per second with an amplitude of 0.001 inch was induced by a solenoid. The specimen with the convex surface was firmly attached to the plunger of the solenoid, which was horizontal. The specimen with the flat surface was held stationary in a horizontal plane and loaded vertically by a flat spring. The spring caused the flat surface to exert a load of approximately 0.2 pound on the convex surface.

The apparatus could be attached to the mechanical stage of a microscope, permitting microscopic observation of the contact area

1213

with vertical or oblique illumination. With transparent flat specimens, the contact area could readily be located because it was surrounded by concentric interference bands (fig. 2). Amplitude was measured by noting the distance between the extreme positions of a scratch mark on the vibrating surface. The experiments conducted at 60 cycles per second were divided into three groups: (1) the preliminary metal against metal, (2) the metal against nonmetal, and (3) the nonmetal against nonmetal. No general material survey was made and the number of metals used was limited.

In the metal-against-metal group, mild steel, chrome steel, stainless steel, copper, and aluminum were vibrated against mild steel essentially to ascertain whether the apparatus would induce fretting corrosion and with satisfactory reproducibiltiy. In the metal-against-nonmetal group, the five metals plus platinum were each vibrated against glass microscope slides, mica, and Lucite and extensive observations were made with 1/2-inch-diameter chrome-alloy steel (SAE 52100) balls and the glass slides. Glass was used as one of the surfaces because it is rigid, noncorrosive, and transparent. These properties were desirable to permit observation of the action as well as to simplify debris analysis. The statement is made in reference 2 that glass not only produces fretting corrosion on steel but is itself attacked; the ability of glass to pick up metal during sliding is demonstrated in reference 5. In the third group, glass, quartz, ruby, mica, and Lucite were each vibrated against one another. All the materials were shaped into convex or flat pieces as required and finished to a surface roughness of 1 to 3 root mean square by fine grinding and polishing.

A group of experiments that are considered to be 1/2-cycle experiments were conducted with an adapter on the apparatus, which provided for sliding the glass microscope slide over the surface of the stationary ball at a speed of approximately 0.002 inch per second or less. The motion was caused by hand-turning a fine screw to which the glass was attached. Because the direction was reversed each 0.001 inch, the frequency was considered 1 cycle per second or less. A slow-motion vibration was thus simulated and the action that occurs in 1/2 cycle was observed.

All specimens were thoroughly cleaned immediately before being mounted in the apparatus. The metal cleaning consisted in degreasing in an organic solvent followed by scrubbing with surgical cotton in a paste of levigated alumina, a thorough rinse in tap water, a rinse in 95-percent alcohol, and drying in air. Particular effort was made to wash off all adhering alumina. The glass, ruby,

quartz, and mica specimens were cleaned in fresh sodium dichromate - sulfuric acid cleaning solution followed by rinse in tap water and distilled water and oven drying. The Lucite was wiped clean with lens tissue.

The number of cycles that any pair of specimens had experienced was determined by measuring the length of time current was supplied to the solenoid. In those cases in which the flat specimens were not transparent, the vibration was induced for periods of 1, 2, 4, 8, 16, 32, 60, 120, 180, 300, and 600 seconds cummulatively. After each period, the flat specimen was removed and the spot on the convex specimen and on the flat specimen were each microscopically examined. Photomicrographs were taken in some cases to aid in the description of the action. When transparent specimens were used, the complete action could be viewed with ease. The vibration could be stopped at any time, however, and the contact area viewed at rest.

RESULTS AND DISCUSSION

Preliminary Metal against Metal

In the preliminary metal-against-metal experiments, each of the several pairs of specimens investigated exhibited fretting corrosion within approximately 300 seconds and produced the characteristic debris and wear area. The pattern of the spot on the flat surface was always similar to the pattern of the spot on the convex surface. These experiments revealed that load, amplitude, and frequency were such as to produce fretting corrosion quickly and the amount of debris and the size of the wear spot could be reproduced for any given pair in the same number of cycles.

The introduction of an oil film increased the time required to produce fretting corrosion but did not otherwise appreciably alter the results.

Metal against Nonmetal

Photomicrographs of the contact area at various stages of the fretting corrosion caused by vibrating a chrome-alloy steel ball against a glass specimen are shown in figure 3. Within 1/4 second (15 cycles), fretting corrosion was evident as a small black irregular spot on the ball, which steadily grew in size and became discontinuous (figs. 3(a) and 3(b)). A brown sticky semifluid oxide was then generated within the contact area, spread over the glass, and adhered tenaciously to it. This oxide shares the contact area

1213

1213

with the black material (figs. 3(b) to 3(f)). A rust-colored fine dry oxide was also formed that was extruded from the area in increasing quantities and accumlated just outside the rubbing area, as evident in figures 3(b) to 3(f). Active black spots shifted position as the phenomenon progressed because of disintegration of peaks bearing the load for the moment.

After approximately 20,000 cycles, the action stablized to a steady-growth condition with continued generation of material in the black spots surrounded by brown semifluid oxide and the formation of fine powder-like oxide. The black color of the active areas indicated the presence of finely divided iron; this indication was further confirmed by subsequent change to dark brown and then to rust brown. If the vibration was stopped, the trapped black material could be seen to gradually turn brown. Finely divided iron, ferrous oxide FeO, and ferrosoferric oxide Fe_3O_4 are black; whereas, ferric oxide Fe_2O_3 and its hydrated form $Fe_2O_3 \cdot H_2O$ are reddish. Because the fretting-corrosion debris of steel was identified by electron diffraction as $Fe_2O_3 \cdot H_2O$, the color changes that occured show the progressive oxidation of the iron. Fretting corrosion is apparently initiated by the loosening, due to inherent adhesive forces, of extremely finely divided and apparently virgin material that is extruded and reacts with oxygen simultaneously. Examination of the ball after the experiment revealed a flat oxide-encrusted spot (fig. 4(a)), which on subsequent cleaning was revealed to be a clean abraded flat spot (fig. 4(b)). The sticky oxide on the glass was removed with difficulty but completely with acids and a striated, cracked area was revealed. The striations could not be brought into sharp focus with the microscope, indicating appreciable depth and irregularity (fig. 5(a)). If the action was continued for longer periods, the glass fragmented locally (fig. 5(b)) and was pitted.

The introduction of a film of pure mineral oil between the surfaces increased the time for the first evidence of fretting-corrosion action 50 times. This delay also provided a slow-motion study of the fretting-corrosion process and showed that oxides were produced in the same manner despite the presence of oil. Once the phenomena were well under way, the modifying effect of the oil was reduced.

Other metals vibrated against glass slides supported the explanation of fretting corrosion deduced from the steel-glass experiments. In one experiment, flame-cleaned platinum foil supported by a steel ball was vibrated in contact with clean glass. The generation of a black powder in the characteristic way was observed (fig. 6). This powder remained black and that which

1213

adhered to the glass could be completely removed only by a 4-hour treatment in aqua regia. Color, acid resistance, and source indicate that the material was finely divided platinum (platinum black). Because platinum will not oxidize in air at any temperature, the theory that oxidation is the primary action of fretting corrosion is not supported.

The action of a stainless-steel (SAE 30705) convex surface against the flat glass was similar to that of the chrome-alloy steel balls except that the number and the extent of the active black areas were greater. Copper produced a brownish-black material that also adhered tenaciously to the glass. At times, large particles of metallic copper could be seen to leave the contact area. During the third minute of vibration, the contact area assumed the greenish tint characteristic of copper oxide. Both these metals were pitted and abraded and the glass striated.

Under the conditions of the 1/2-cycle experiment two types of action were observed. If the surface of the ball was previously roughened with 2/0 emery paper, the glass would polish the contact area on the ball and become smeared with the semifluid oxide, which would again tenaciously adhere to the glass. The amount of debris accumulated in three 1/2 cycles of vibration is shown in figure 7(a).

An increase in frictional force was apparent when the oxide was present between the surfaces. This greater motivating force was required to continue relative sliding because a nonlubricating material was present between the surfaces and tenaciously adhered to each. The oxide itself was sheared and the two new faces thus formed became the sliding surfaces. If a ball with its original polished surface was used, much less oxide would be smeared, but the movement would cause the glass to grip the ball and as the relative sliding continued the glass would visibly and audibly crack. The cracking occurred at the trailing edge of the contact area. A photomicrograph of the glass through which the picture was taken in the process of forming a second crack is shown in figure 7(b). The row of cracks produced in the glass during continued sliding is shown in figure 7(c). The smearing of the metallic oxide onto the glass and the cracking of the glass are apparently due to a great amount of adhesion permitted by the extreme cleanliness of the specimens. The surface finish on the ball determines which phenomenon will occur. A rough surface supports the load on a number of peaks, the average particle of which is relatively exposed. Sliding of the smooth glass over these peaks results in disintegration of the peaks and subsequent

oxidation of the removed metal. A smooth polished surface on the ball supports the load on a few broad undulations, the material of which is secure. Sliding of the smooth glass over these contact areas results in failure of the glass rather than the metal. This concept is in agreement with reference 7, which presents data to show that the amount of material transferred from base to rider increased with increase in surface roughness if the rider was harder than the base. Considering the steel ball as the rider and the steel harder than the glass, some incongruity may exist in this comparison in that the glass picked up material from the steel.

The glass appeared to plough into the aluminum scoring it heavily. Large metallic pieces were mixed with a grayish-black powder. Some of the debris adhered tenaciously to the glass in the characteristic manner. The powder was insoluble in nitric acid but soluble in alkali, indicating that aluminum was still present. Mica and Lucite always wore away the metal surfaces and produced very great amounts of flocculent debris. Observation of the action of the metals was difficult because of the great dilution of the metal debris by the voluminous debris from the flat specimen. This experiment indicated that no property peculiar to glass was inducing the action.

Nonmetals against Nonmetals

The independence of fretting corrosion from chemical action was indicated in a group of experiments involving the nonmetallic, nonoxidizing materials glass against quartz, ruby, or mica. By vibrating a ruby with a convex surface against a glass slide and observing the action under a microscope, surface disintegration could be seen to occur. The glass, after 2 to 3 seconds of rubbing, suddenly collapsed locally and distributed debris about the contact area, leaving a pit. This action shifted the bearing area to the edge of the pit and the disintegration was continued (fig. 8). An early stage of disintegration with two pits formed is shown in figure 8(a) whereas the advanced stage of 20 or more pits is shown in figure 8(b). The ruby was simply further polished, that is, the microscopic scratches were erased. The vibration was not continued long enough to pit the ruby. Quartz against glass acted the same as ruby against glass. Mica against a glass ball and Lucite against a glass ball also behaved similarly. In all cases, the debris was produced, extruded, and accumulated in the same manner observed with metal debris, except that no change in color took place. Fretting corrosion occurred to mica in the least number of cycles, the number required being progressively greater for Lucite, glass, quartz, and ruby, which is also the order of increasing hardness of the

materials. The tendency for fretting corrosion between the various nonmetals and glass and the amount of debris generated therefore appear to be inversely proportional to the hardness of the nonmetal.

CONCLUDING REMARKS

The observations made indicate that fretting corrosion can occur between two nonmetals. The susceptibility to fretting corrosion of nonoxidizing materials such as glass, quartz, ruby, mica, and platinum relegates the role of oxidation as a cause to that of a secondary factor and indicates that finely divided and apparently virgin material is first produced. In the metals, this production of virgin metal is suggested by the color changes through which the metal passed as it oxidized. The oxides are therefore considered a byproduct of the initial action. The spontaneity of the oxidation is probably due to the increased chemical activity of the particles. This increase is called mechanical activation in reference 9, which also states that the increase is more than that produced by cleanliness or reduced particle size. The oxide formation was induced at extremely low speeds and light loads where the dissipation of frictional heat is sufficiently rapid to minimize the occurrence of local hot spots. The possibility of fretting corrosion being caused by regenerative high-temperature forming oxide films that are then rubbed off is therefore unlikely.

The conclusion is made in reference 2 that alternating slip is a necessary condition for fretting corrosion. The production of a smear on the glass surface in 1/2 cycle and the cracking of glass on smooth metal indicate that alternation of motion is unnecessary to promote the action that causes fretting corrosion, although alternation does give it its usual characteristics. This idea is supported by the observation that fretting corrosion starts with the sliding. Lowering the frequency only decreases the rate at which fretting corrosion occurs. This relation indicates that the cause of fretting corrosion is independent of frequency.

The metal transfer caused by sliding one metal over another demonstrated in references 7 and 9 was attributed to adhesion. Similarly, in the experiments reported herein the action observed, namely, removal of material, cracking, and general surface destruction was attributed to adhesion, which leads to the conclusion that fretting corrosion is a manifestation of the adhesion component of friction.

RESULTS AND CONCLUSIONS

An experimental investigation was conducted to determine the cause of fretting corrosion. Glass and other noncorrosive materials were vibrated in contact with one another and with metals and microscopic observation of the action was made. Convex surfaces were vibrated in contact with stationary flat surfaces at frequencies of 60 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

The following results and conclusions were indicated:

1. Fretting corrosion was caused by the removal of finely divided and apparently virgin material due to inherent adhesive forces.

2. The fretting corrosion of platinum, glass, quartz, ruby, and mica relegated the role of oxidation as a cause to that of a secondary factor.

3. Fretting corrosion readily occurred between clean nonmetals and metals. Glass microscope slides and steel balls provided an excellent method for observing fretting corrosion.

4. The initiating of fretting corrosion is independent of vibratory motion or high sliding speeds.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 31, 1949.

REFERENCES

1. Anon.: The Corrosion Handbook, Herbert H. Uhlig, ed. John Wiley & Sons, Inc., 1948, pp. 590-597.

2. Tomlinson, G. A., Thorpe, P. L., and Gough, H. J.: An Investigation of the Fretting Corrosion of Closely Fitting Surfaces. Proc. Inst. Mech. Eng., vol. 141, 1939, pp. 223-249.

3. Tomlinson, G. A.: A Molecular Theory of Friction. Phil. Mag. and Jour. Sci., Suppl., ser. 7, vol. 7, no. 46, June 1929, pp. 905-939.

4. Sakmann, B. W., Rightmire, B. G.: An Investigation of Fretting Corrosion under Several Conditions of Oxidation. NACA TN 1492, 1948.

5. Morton, Hudson T.: Friction Oxidation. The Fafnir Bearing Co. (New Britain, Conn.).

6. Dies, Kurt: Fretting Corrosion, a Chemical-Mechanical Phenomenon. Eng. Digest, vol. 5, no. 11, Nov. 1944, p. 324. (From V.D.I. Zeitschr., vol. 87, no. 29-30, July 1943, pp. 475-476.)

7. Sakmann, B. W., Burwell, J. T., Jr., and Irvine, J. W., Jr.: Measurements of the Adhesion Component in Friction by Means of Radioactive Indicators. Jour. Appl. Phys., vol. 15, no. 6, June 1944, pp. 459-473.

8. Shaw, M. C.: Mechanical Activation - A Newly Developed Chemical Process. Jour. Appl. Mech., vol. 15, no. 1, March 1948. pp. 37-44.

9. Bowden, F. P., Moore, A. J. W., and Tabor, D.: The Ploughing and Adhesion of Sliding Metals. Jour. Appl. Phys., vol. 14, no. 2, Feb. 1943, pp. 80-91.

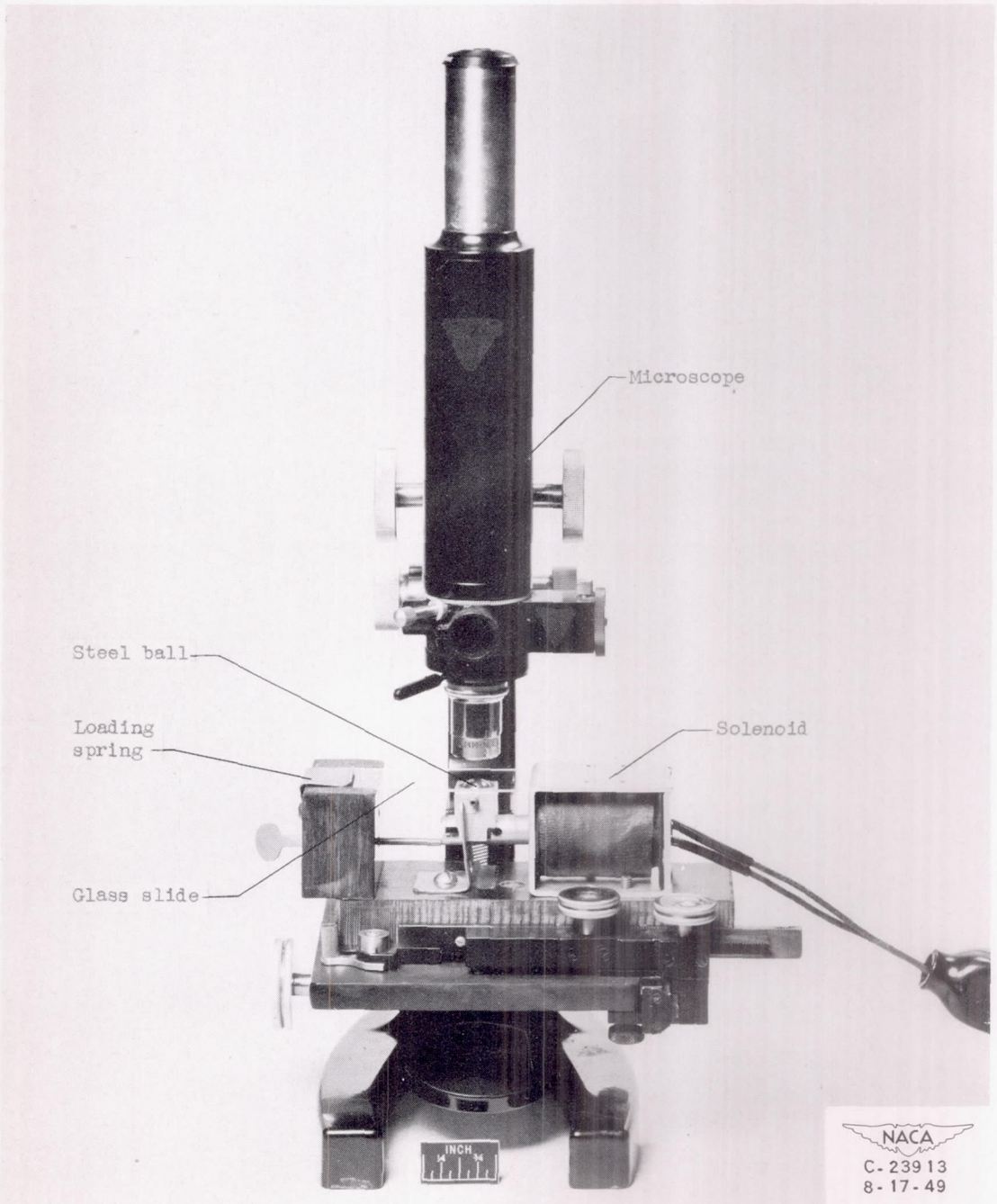


Figure 1. - Fretting-corrosion apparatus.

1213

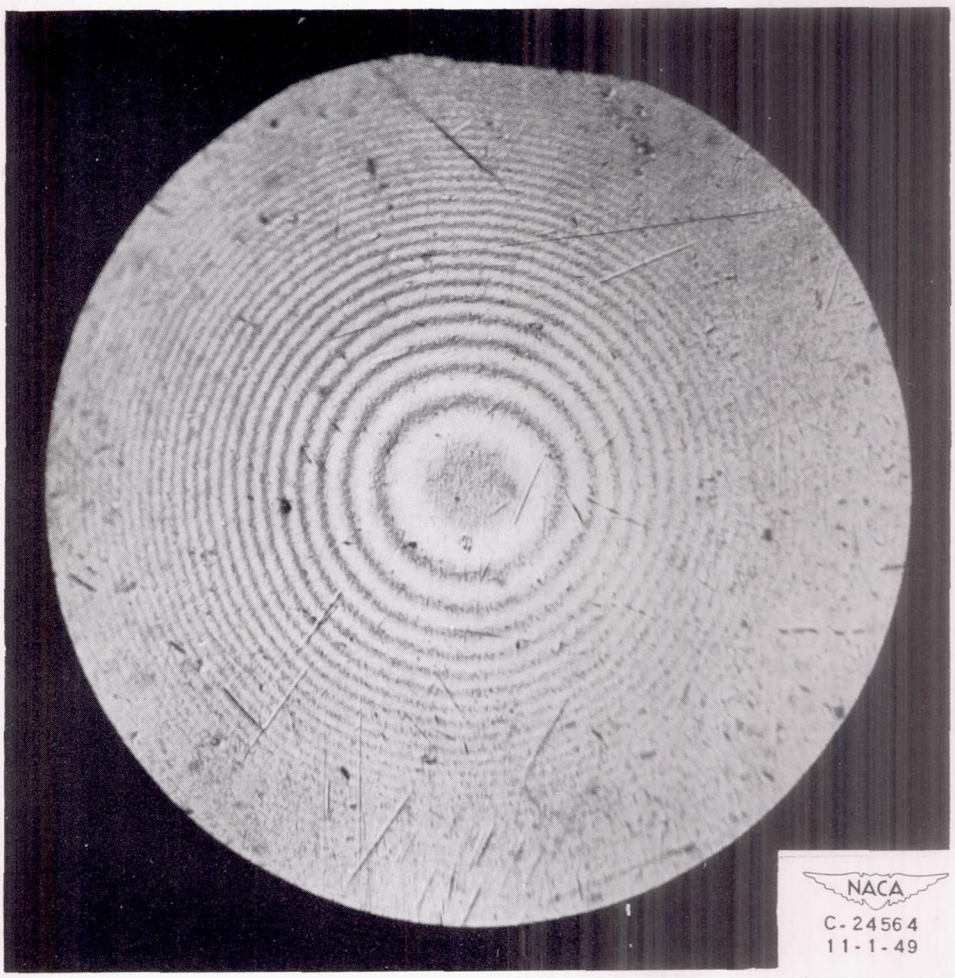
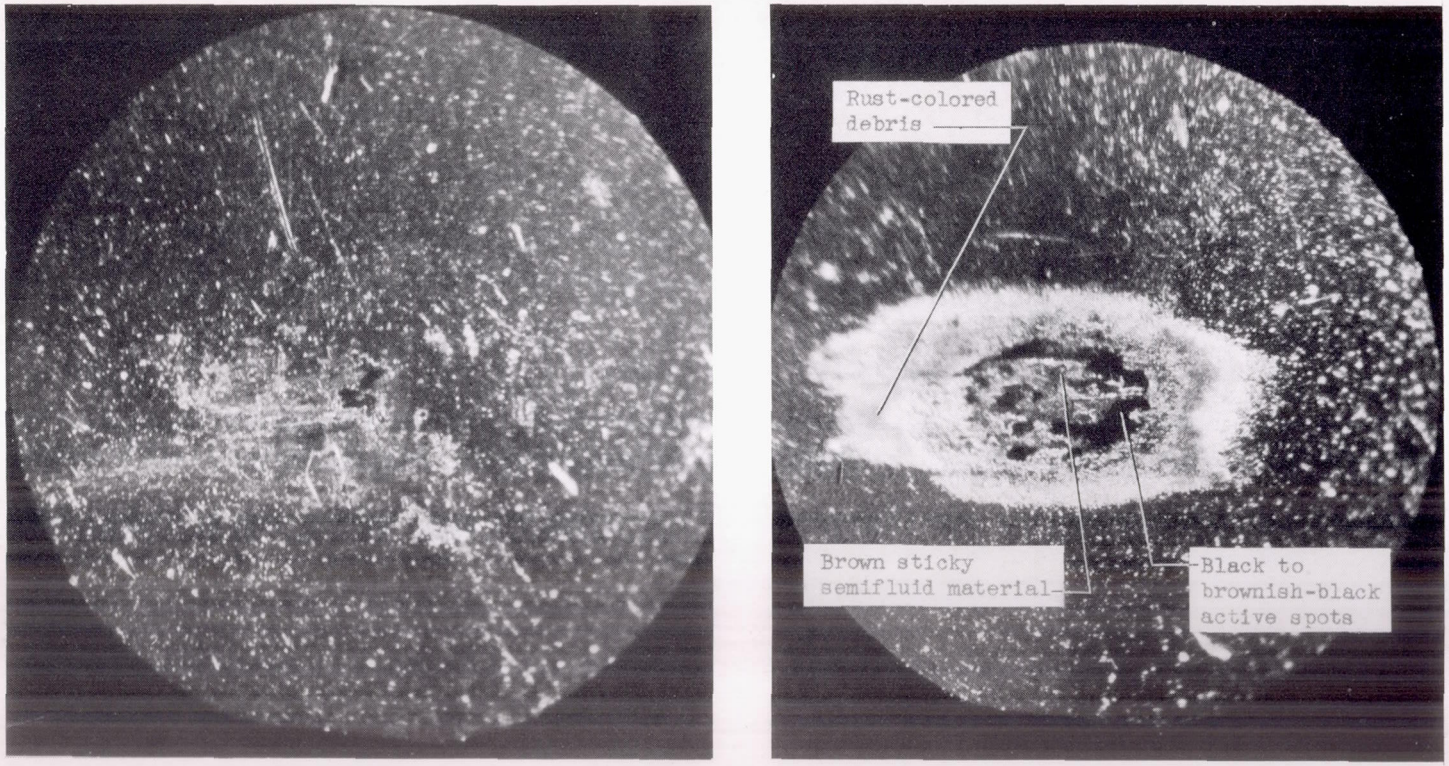


Figure 2. - Photomicrograph of chrome-alloy steel ball through glass slide showing interference bands surrounding contact area. X140.

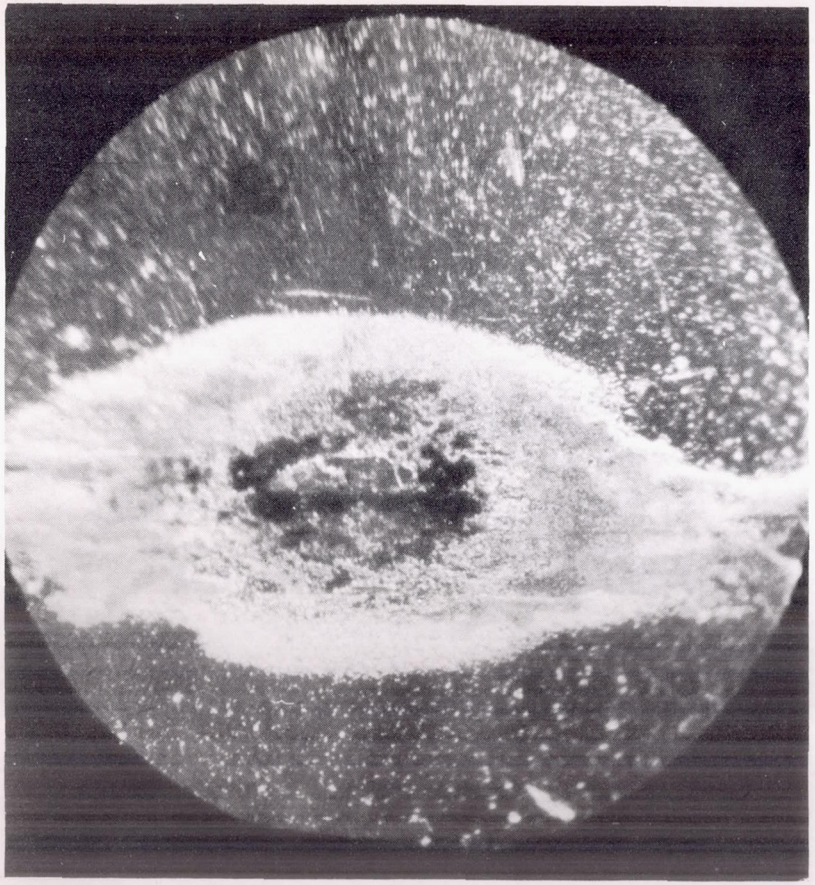


(a) Cycles, 15

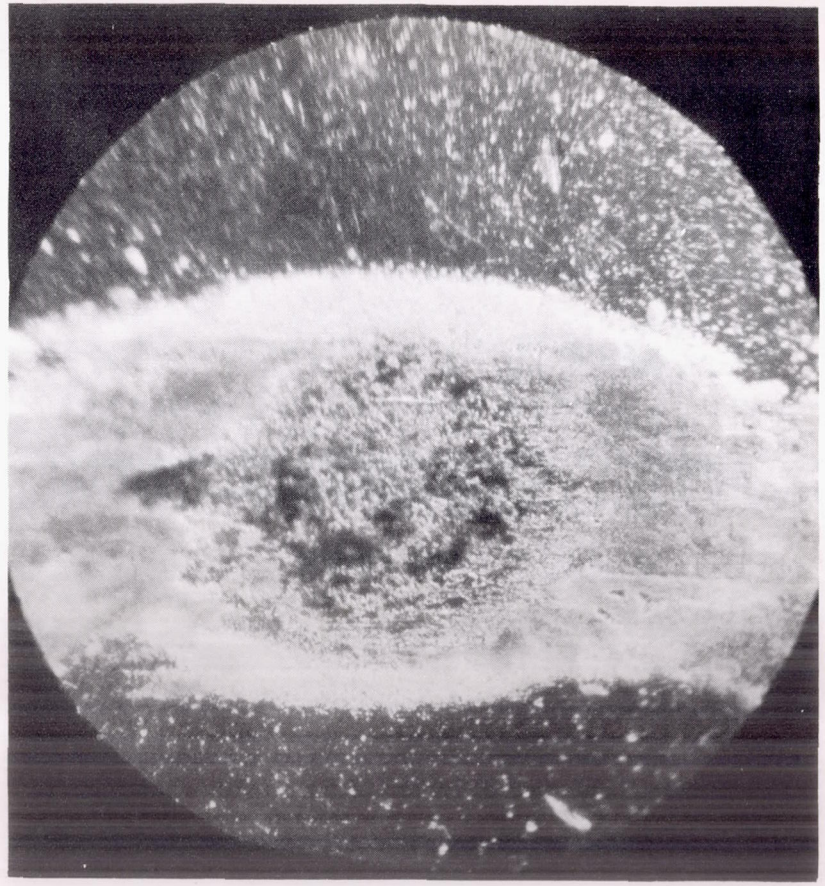
(b) Cycles, 60

NACA
C-24565
11-1-49

Figure 3. - Photomicrographs showing progressive stages in fretting corrosion between glass microscope slide and chrome-alloy steel ball. X140.



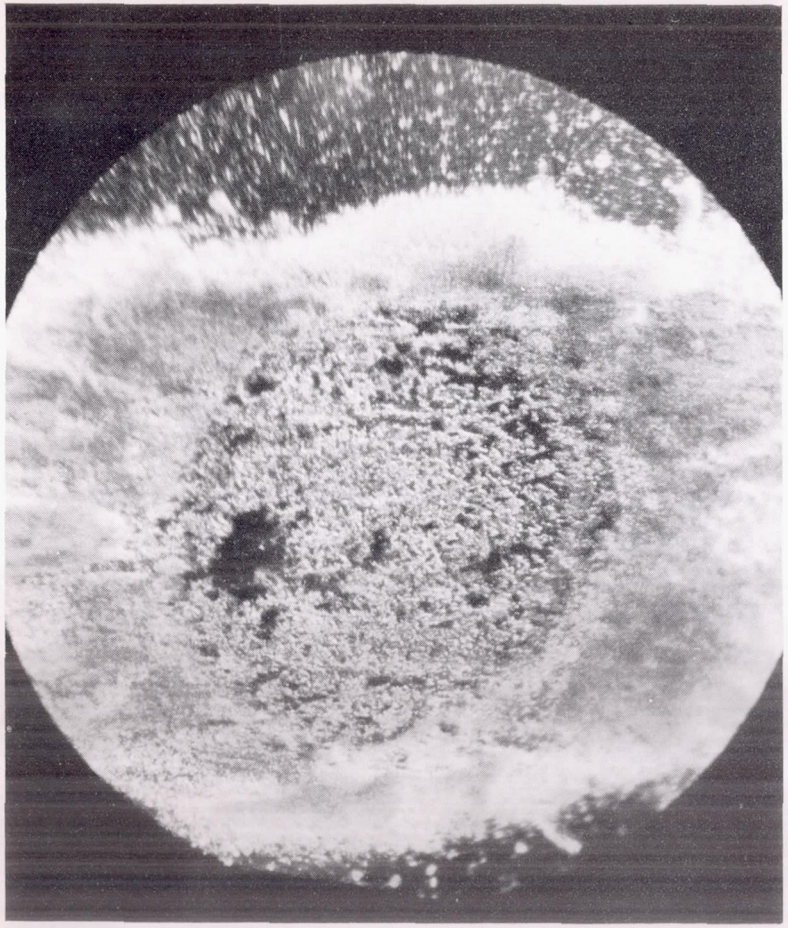
(c) Cycles, 120



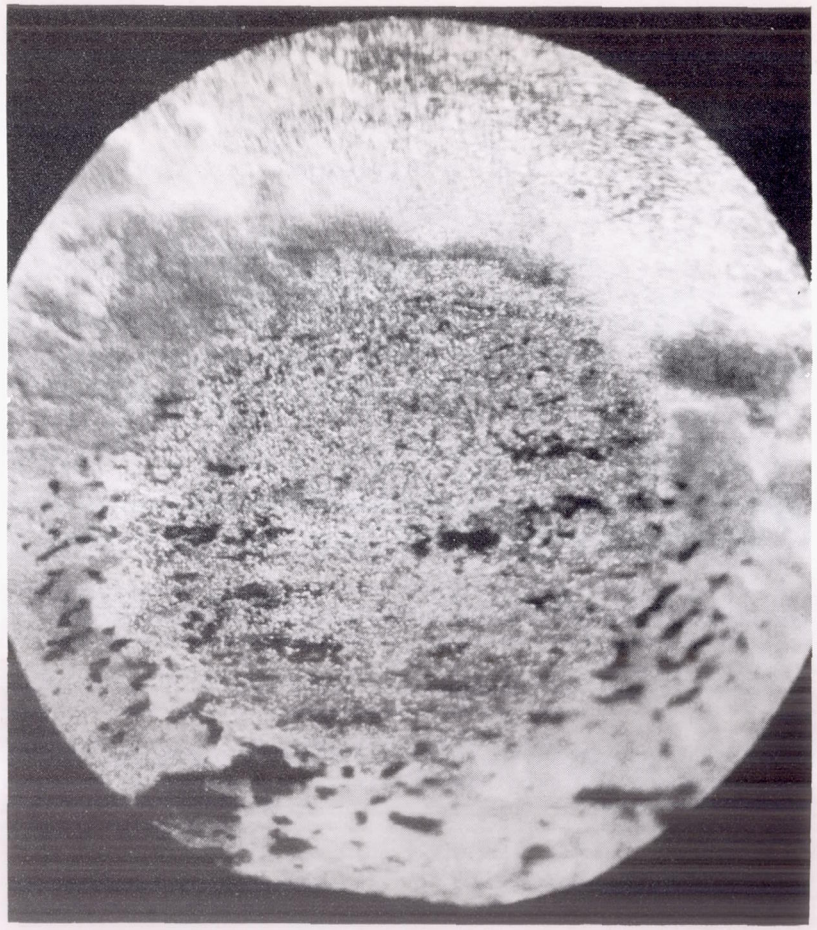
(d) Cycles, 360

NACA
C-24566
11-1-49

Figure 3. - Continued. Photomicrographs showing progressive stages in fretting corrosion between glass microscope slide and chrome-alloy steel ball. X140.



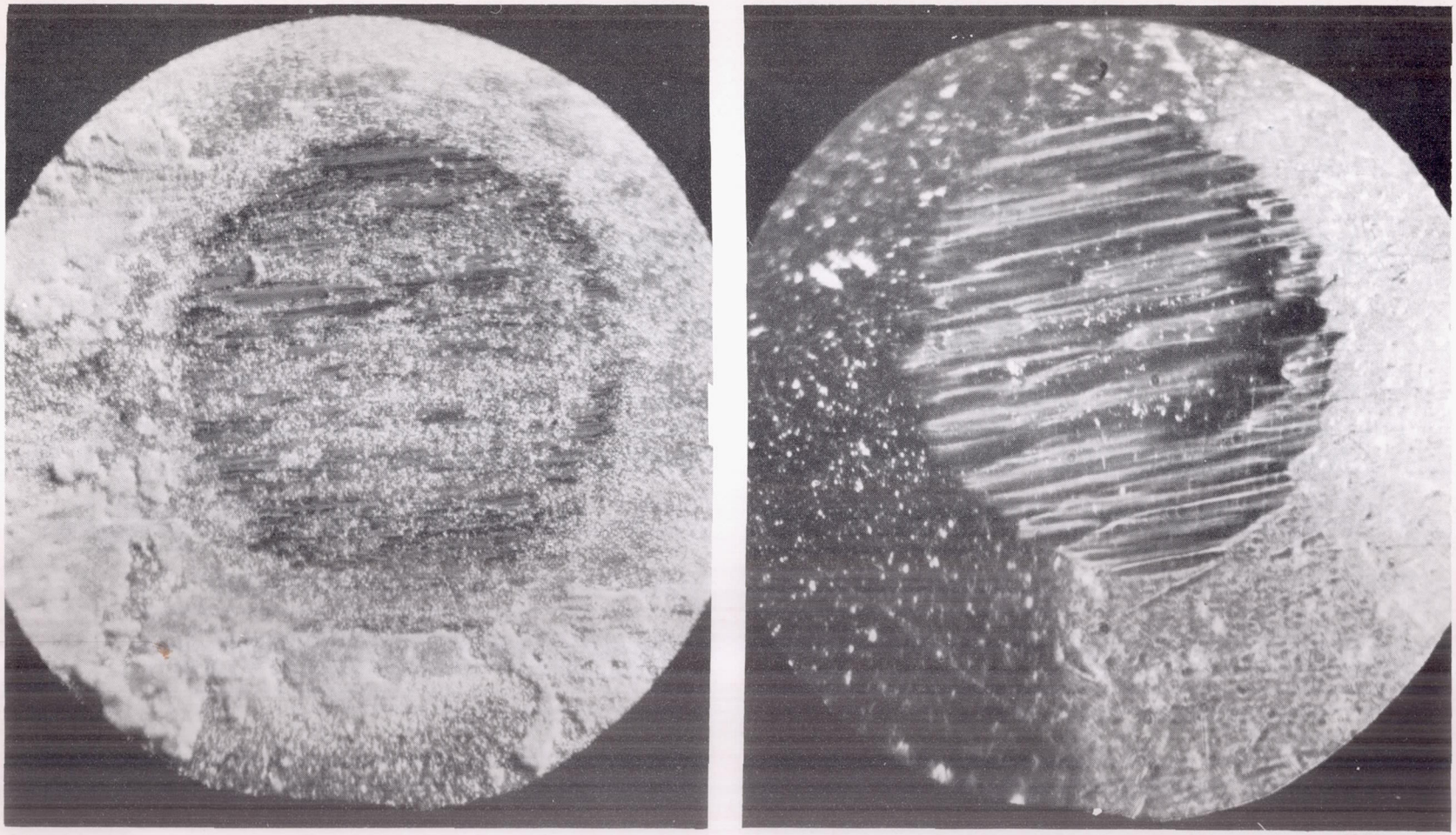
(e) Cycles, 600



(f) Cycles, 1800

NACA
C-24567
11-1-49

Figure 3. - Concluded. Photomicrographs showing progressive stages in fretting corrosion between glass microscope slide and chrome-alloy steel ball. X140.



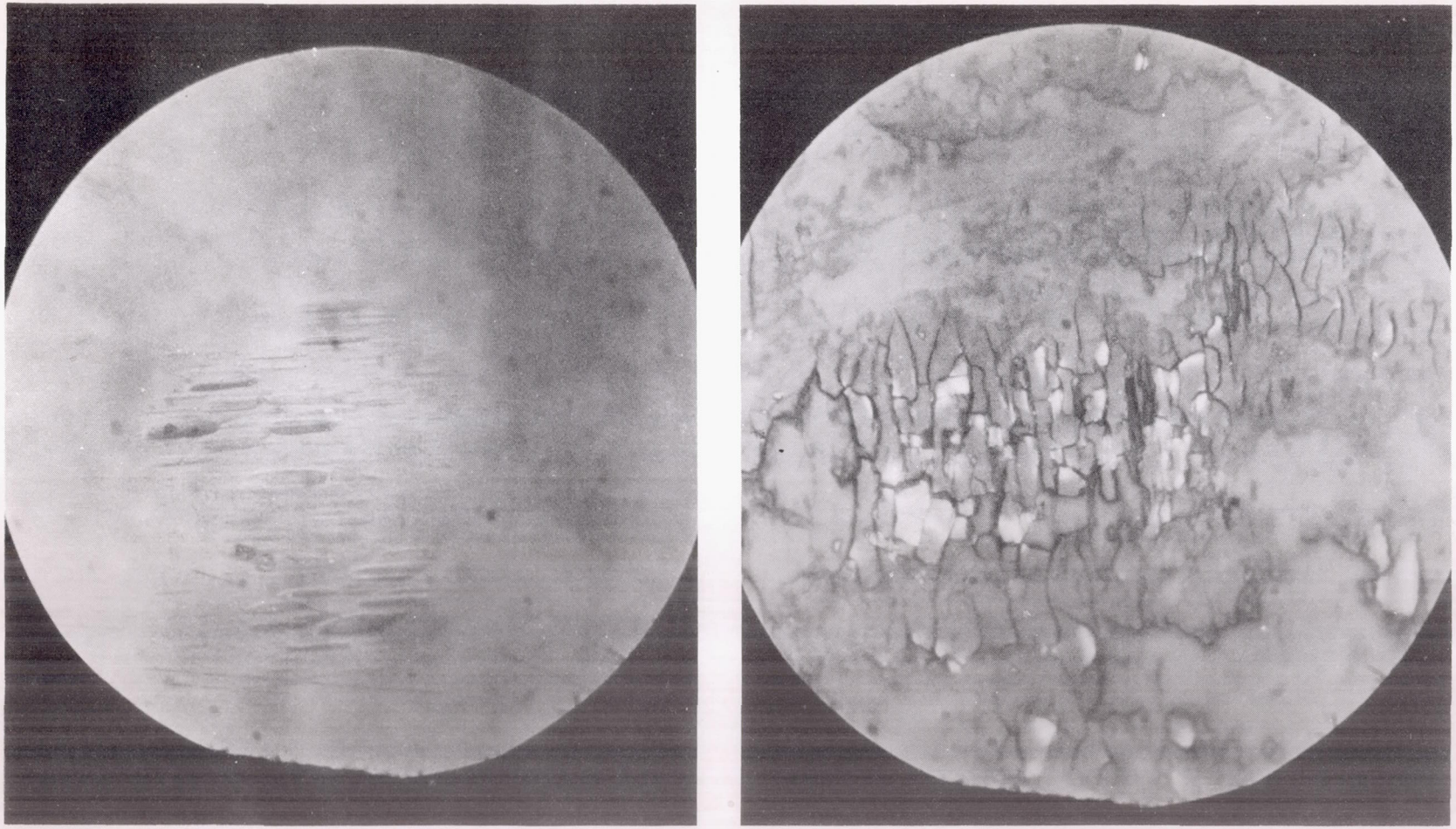
(a) Before cleaning.

(b) After cleaning.

NACA

C-24568
11-1-49

Figure 4. - Photomicrographs showing fretting-corrosion area on chrome-alloy steel ball after 1800 cycles. X140.

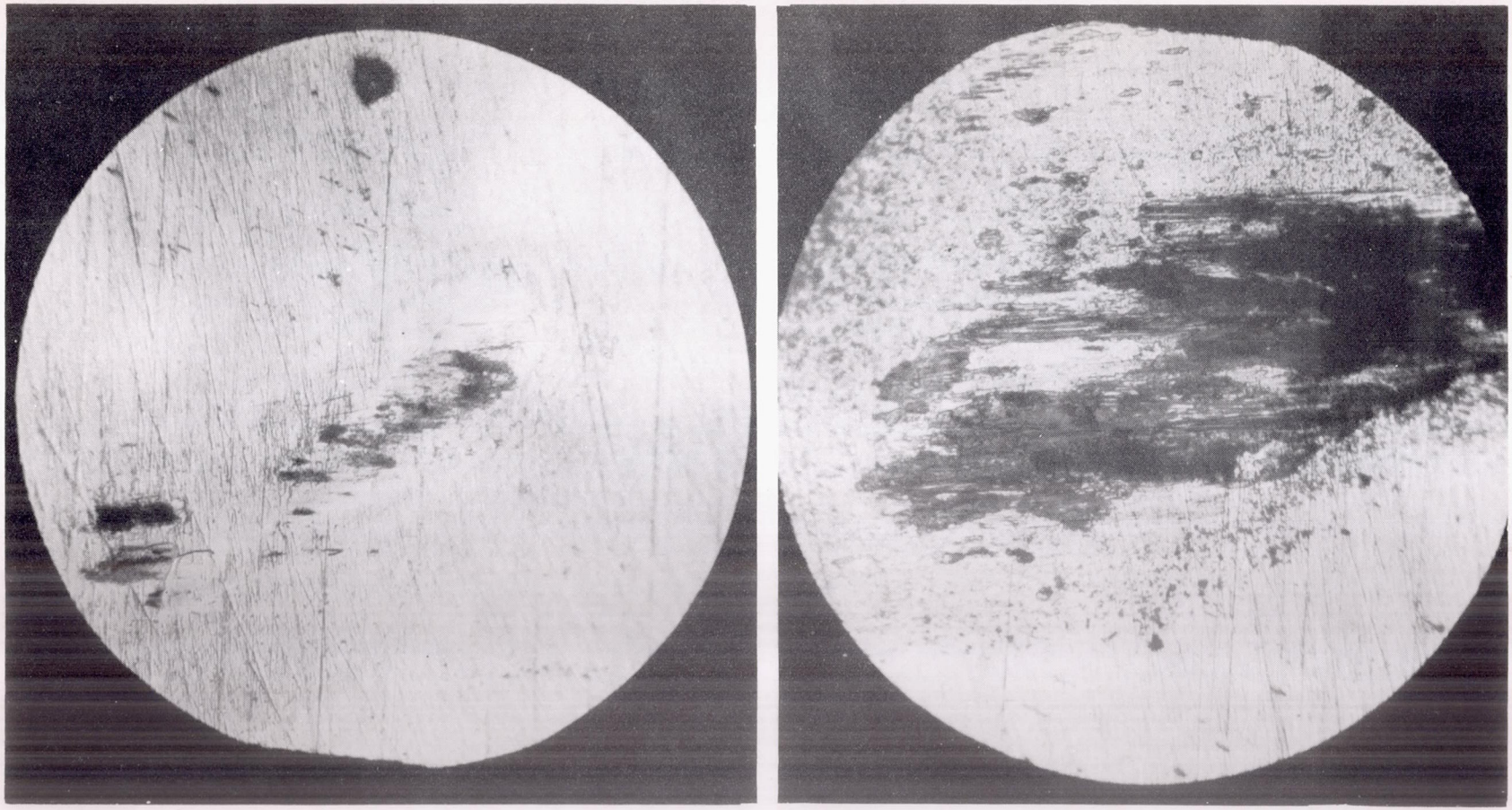


(a) Early stage, X140.

(b) Later stage, X300.

NACA
C-24569
11-1-49

Figure 5. - Photomicrographs of cleaned wear area on glass showing cracking and striations produced by vibration of contacting chrome-alloy steel ball.

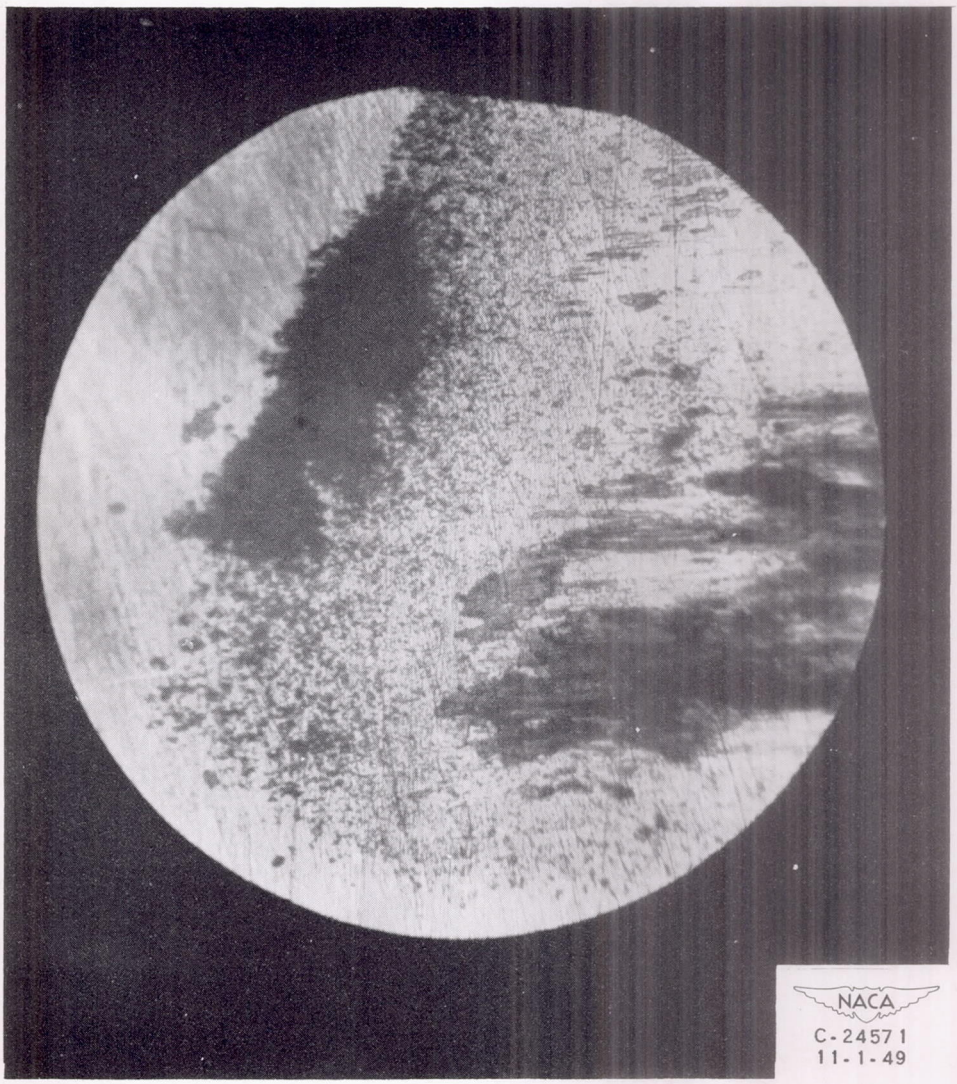


(a) Early stage.

(b) Advanced stage.

NACA
C-24570
11-1-49

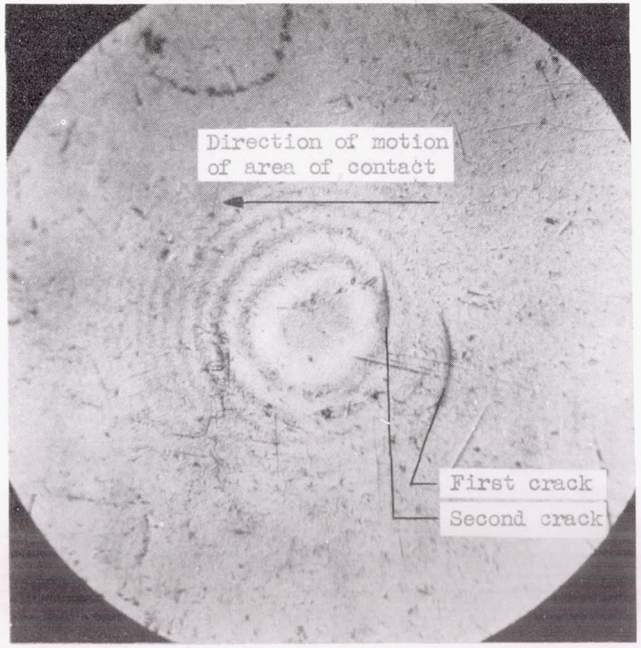
Figure 6. - Photomicrographs of convex platinum surface through glass slide showing wear and debris produced. X140.



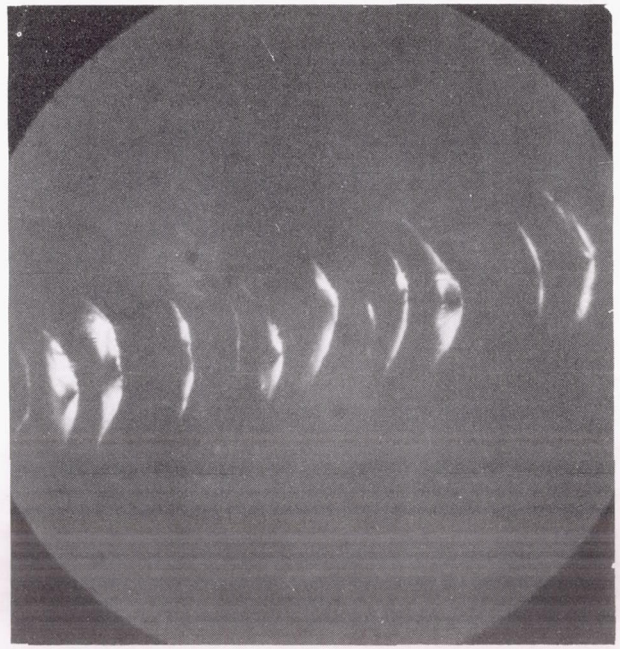
(c) Debris accumulation outside field of view of figure 6(b).

Figure 6. - Concluded. Photomicrographs of convex platinum surface through glass slide showing wear and debris produced. X140.

(a) View of glass slide showing amount of debris transferred from roughened steel.



(b) View of ball through glass showing second crack being formed in glass on trailing edge of area of contact.

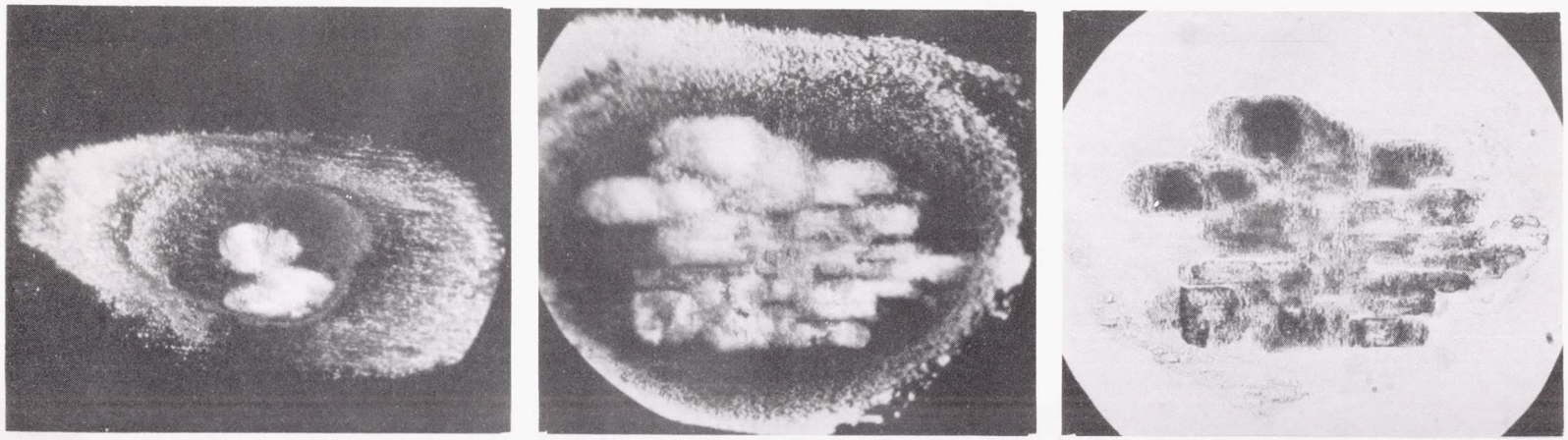


(c) View of glass slide showing resultant row of cracks.

NACA
C-24572
11-1-49

Figure 7. - Photomicrographs showing effects of one-half cycle vibration between glass and steel surface. X140.

NACA-Langley - 2-28-50 - 1050



(a) Early stage.

(b) Advanced stage.

(c) Advanced stage after removal of debris.

NACA

C-24573
11-1-49

Figure 8. - Photomicrographs showing results of fretting corrosion between ruby and glass. X140.